



CTP

Center for Theoretical Physics
SEOUL NATIONAL UNIVERSITY

Composite resonances at a multi-TeV muon collider

A study for the minimal composite Higgs model

Ke-Pan Xie [Seoul National University, Korea]

2021.4.18 @APS April meeting (online)

In collaboration with Da Liu and Lian-Tao Wang, in progress

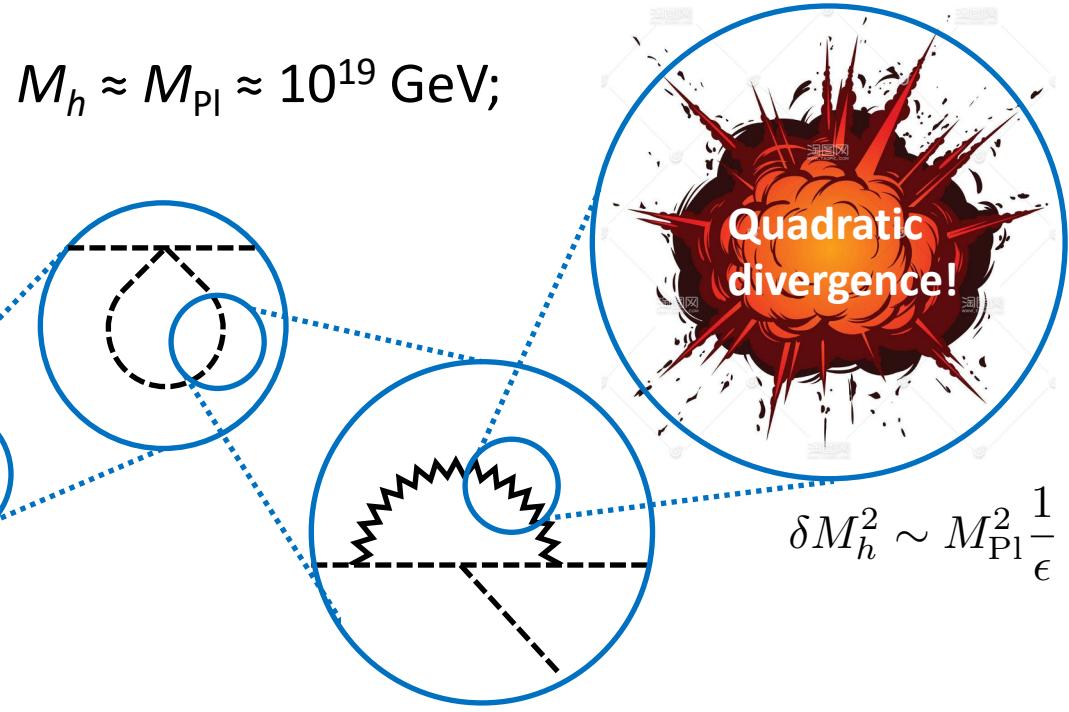
• The hierarchy problem

The mass of **an elementary scalar** is sensitive to the **high scale new physics** correction;

Therefore, “Naturally” $M_h \approx M_{\text{Pl}} \approx 10^{19} \text{ GeV}$;

Three Generations of Matter (Fermions)			
I	II	III	
mass = $2.4 \text{ MeV}/c^2$ charge = $\frac{2}{3}$ spin = $\frac{1}{2}$ name = u	mass = $1.27 \text{ GeV}/c^2$ charge = $\frac{2}{3}$ spin = $\frac{1}{2}$ name = c	mass = $171.2 \text{ GeV}/c^2$ charge = $\frac{2}{3}$ spin = $\frac{1}{2}$ name = t	mass = 0 charge = 0 spin = 1 name = H
Quarks			photon
mass = $4.8 \text{ MeV}/c^2$ charge = $-\frac{1}{3}$ spin = $\frac{1}{2}$ name = d	mass = $104 \text{ MeV}/c^2$ charge = $-\frac{1}{3}$ spin = $\frac{1}{2}$ name = s	mass = $4.2 \text{ GeV}/c^2$ charge = $-\frac{1}{3}$ spin = $\frac{1}{2}$ name = b	mass = 0 charge = 0 spin = 1 name = g
Leptons			Gauge Bosons
mass = $<2.2 \text{ eV}/c^2$ charge = $\frac{1}{2}$ spin = $\frac{1}{2}$ name = e	mass = $<0.17 \text{ MeV}/c^2$ charge = $\frac{1}{2}$ spin = $\frac{1}{2}$ name = μ	mass = $<15.5 \text{ MeV}/c^2$ charge = $\frac{1}{2}$ spin = $\frac{1}{2}$ name = τ	mass = $91.2 \text{ GeV}/c^2$ charge = 0 spin = 1 name = Z⁰
mass = $0.511 \text{ MeV}/c^2$ charge = -1 spin = $\frac{1}{2}$ name = e	mass = $105.7 \text{ MeV}/c^2$ charge = -1 spin = $\frac{1}{2}$ name = μ	mass = $1.777 \text{ GeV}/c^2$ charge = -1 spin = $\frac{1}{2}$ name = τ	mass = $80.4 \text{ GeV}/c^2$ charge = ± 1 spin = 1 name = W[±]

The Standard Model
(Higgs is elementary)



But in the reality: $M_h = 125 \text{ GeV}!$
Why is the Higgs so light?

• Composite Higgs model as a solution

If the Higgs is a composite Nambu-Goldstone boson (NGB) from the spontaneous symmetry breaking G/H of a strong interacting sector...

Then by **Goldstone theorem** it is naturally light. [Kaplan, NPB1991]

Three Generations of Matter (Fermions)			
I	II	III	
mass = $2.4 \text{ MeV}/c^2$	$1.27 \text{ GeV}/c^2$	$171.2 \text{ GeV}/c^2$	
charge = $\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	
spin = $\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	
name ...	U up	C charm	t top
Quarks			
mass = $4.8 \text{ MeV}/c^2$	$104 \text{ MeV}/c^2$	$4.2 \text{ GeV}/c^2$	
charge = $-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	
spin = $\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	
name ...	d down	s strange	b bottom
Leptons			
mass = $<2.2 \text{ eV}/c^2$	$<0.17 \text{ MeV}/c^2$	$<15.5 \text{ MeV}/c^2$	
charge = 0	$\frac{1}{2}$	$\frac{1}{2}$	
spin = $\frac{1}{2}$	e electron	ν_μ muon neutrino	ν_τ tau neutrino
Gauge Bosons			
mass = $91.2 \text{ GeV}/c^2$	0	0	1
charge = 0	$\frac{1}{2}$	$\frac{1}{2}$	1
spin = 1	Z boson		
mass = $0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$80.4 \text{ GeV}/c^2$
charge = -1	-1	$\frac{1}{2}$	$\pm\frac{1}{2}$
spin = $\frac{1}{2}$	e electron	μ muon	τ tau
			W^\pm W boson

But the Higgs cannot be an exact NGB!

It needs to have a potential to break the EW symmetry

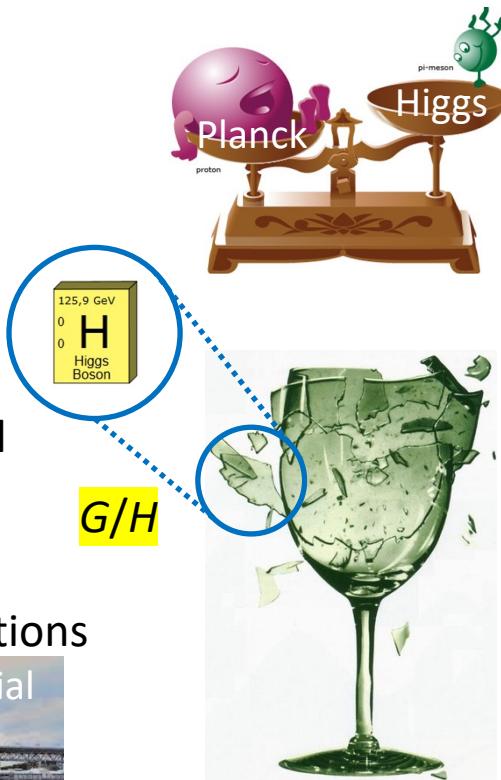
Explicit G -breaking interactions

Generate the Higgs potential



The elementary sector
(SM without Higgs)

The composite sector
(New strong dynamics)



• The minimal composite Higgs model

The strong dynamics: $G/H = \text{SO}(5)/\text{SO}(4)$ [Agashe *et al*, NPB2005]

Broken generators: $10 - 6 = 4$: pseudo-NGBs as the Higgs doublet

$$\begin{aligned}\mathcal{L}_{\text{MCHM}} = & \mathcal{L}_{\text{strong}} + \mathcal{L}_{\text{SM}} \\ & + \mathcal{J}_\mu^{a_L} W_{a_L}^\mu + \mathcal{J}_{Y_\mu} B^\mu + y_L \bar{q}_L \mathcal{O}_R + y_R \bar{u}_R \mathcal{O}_L\end{aligned}$$

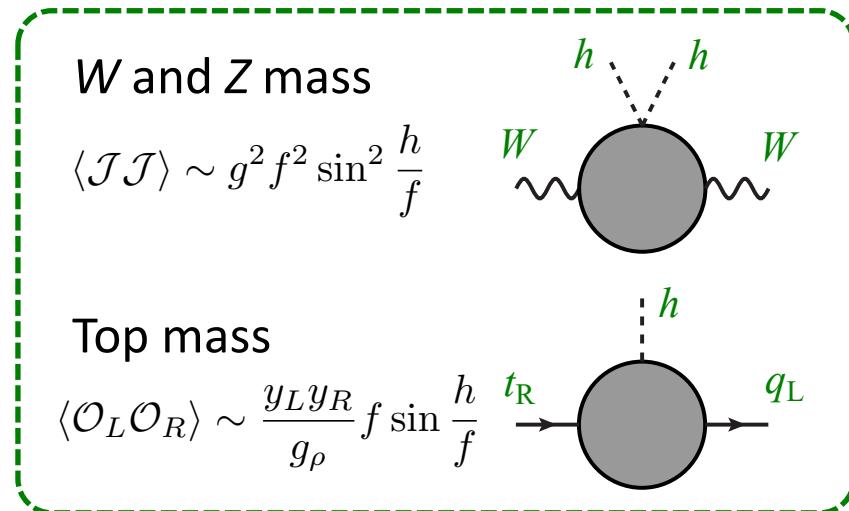
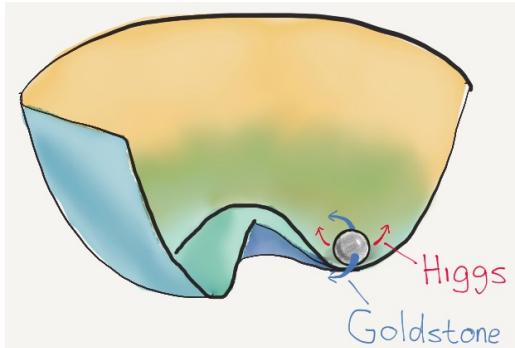
EW gauge coupling:

Subgroup $\text{SU}(2)_L \times \text{U}(1)_Y$ gauged

Partial compositeness: q_L and u_R fill
in the incomplete rep. of $\text{SO}(5)$

$$V_{\text{eff}}(h) \approx \alpha \sin^2 \frac{h}{f} - \beta \sin^2 \frac{h}{f} \cos^2 \frac{h}{f} \quad \parallel \quad \text{EWSB} \rightarrow \quad \sin^2 \frac{\langle h \rangle}{f} = \frac{\beta - \alpha}{2\beta}$$

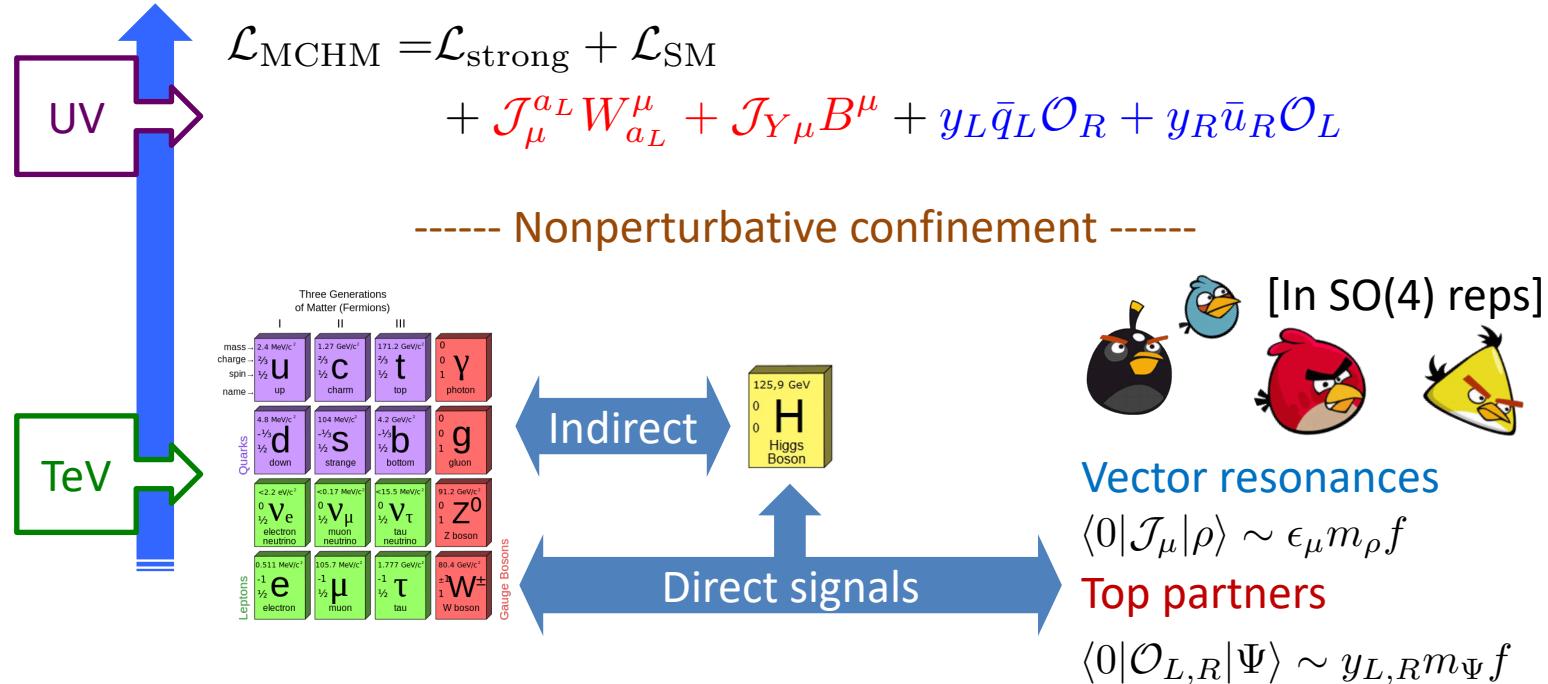
Higgs potential generated;
EWSB triggered



• Phenomenology of the composite Higgs model

The strong dynamics: $\text{SO}(5)/\text{SO}(4)$ [Agashe *et al*, NPB2005]

Broken generators: $10 - 6 = 4$: pseudo-NGBs as the Higgs doublet



We focus on the direct search.

Resonances mass around 1-10 TeV, might be detected at current or future colliders!

This talk: a multi-TeV muon collider

• The vector resonance

The $\rho^{\pm,0}$ -resonance: (3,1) of SO(4) [same with W^a]:

$$\mathcal{J}_\mu^a W_a^\mu \rightarrow -a_\rho^2 f^2 g_\rho \rho_\mu^a \left(g_2 W_\mu^a - \frac{i}{f^2} H^\dagger \frac{\sigma^a}{2} \overleftrightarrow{D}_\mu H \right)$$

SU(2)_L gauge coupling

Order 1 parameter **SO(5)/SO(4) decay constant** **Strong dynamics coupling**

$$g_\rho \sim \frac{4\pi}{\sqrt{N}}$$

ρ mass term & the ρ - W mixing angle

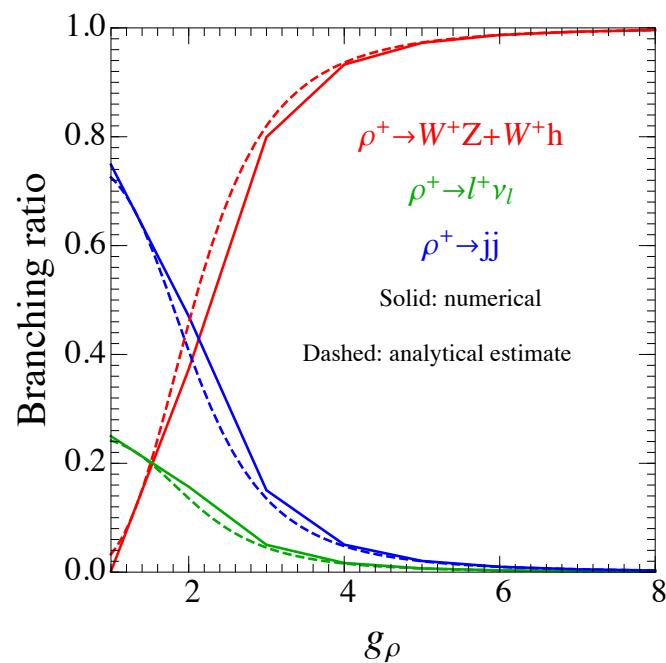
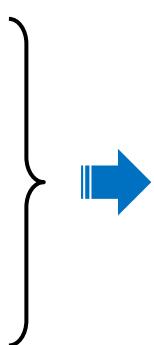
$$\boxed{\frac{1}{2}(a_\rho g_\rho f)^2 \rho_\mu^a \rho_a^\mu} \quad \sin \theta \sim \frac{g_2}{\sqrt{g_\rho^2 + g_2^2}} \approx \frac{g_2}{g_\rho}$$

The ρ -elementary quark coupling

$$g_{\rho f_L \bar{f}_L^{(\prime)}} = g_2 \sin \theta \sim \frac{g_2^2}{g_\rho}$$

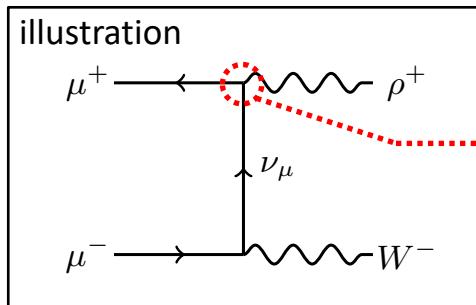
The ρ -Goldstone coupling

$$\sim g_\rho \rho_\mu^a H^\dagger \frac{\sigma^a}{2} i \overleftrightarrow{D}_\mu H$$



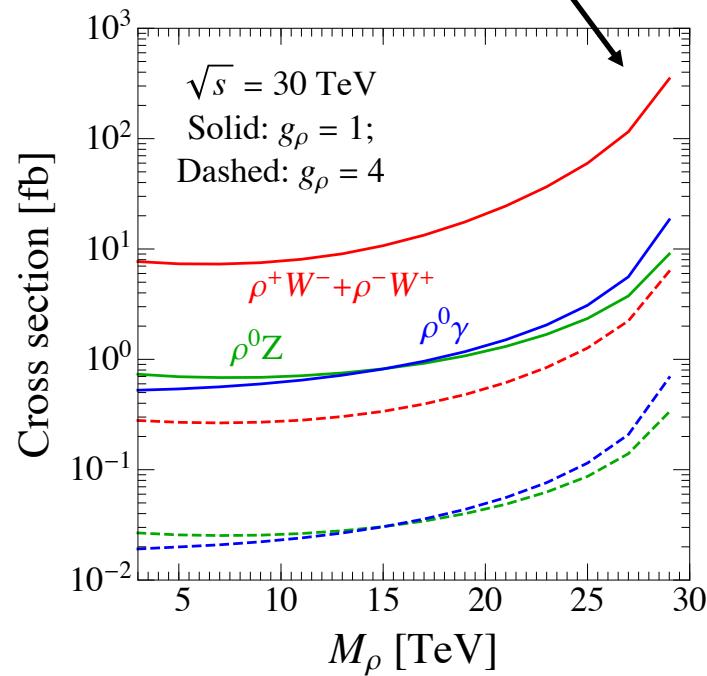
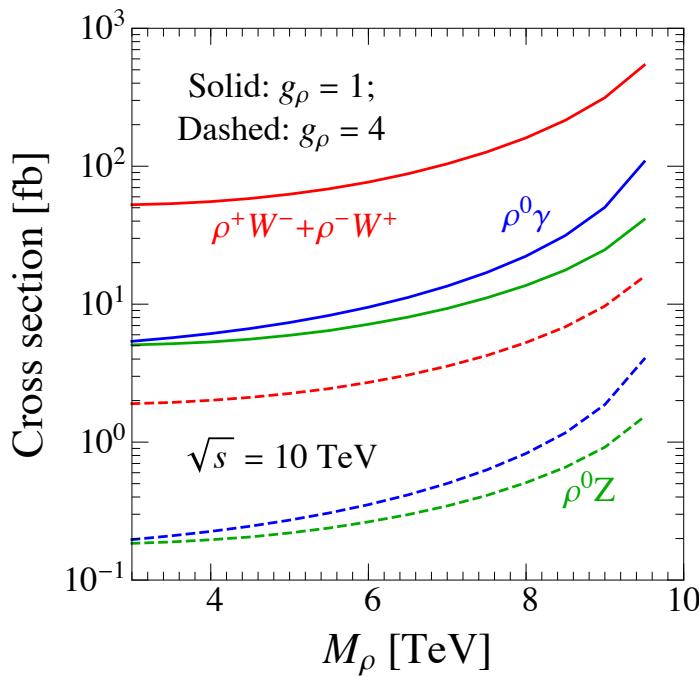
- Producing the vector resonances at muon colliders

The ρV associated production, with $V = W^\pm, Z, \gamma$.



$$g_{\rho f_L \bar{f}_L^{(\prime)}} = g_2 \sin \theta \sim \frac{g_2^2}{g_\rho}$$

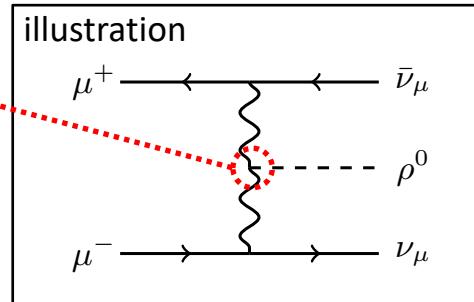
Enhancement when the t -channel light fermion tends to be on-shell



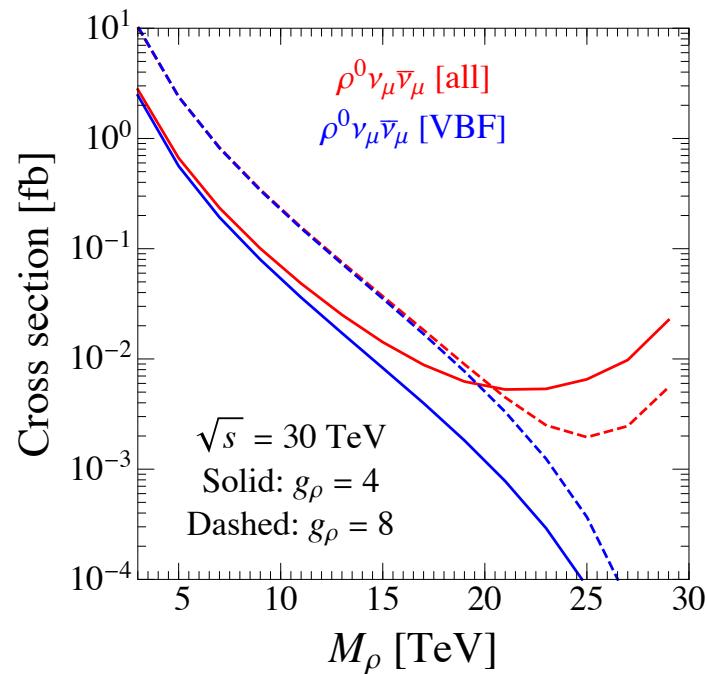
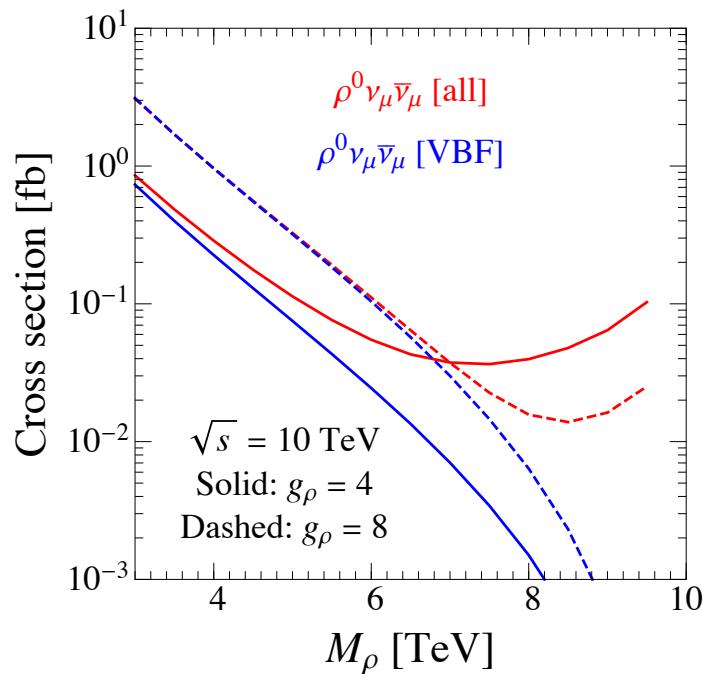
- Producing the vector resonances at muon colliders

The vector boson fusion (VBF).

$$\sim g_\rho \rho_\mu^a H^\dagger \frac{\sigma^a}{2} i \vec{D}_\mu H$$



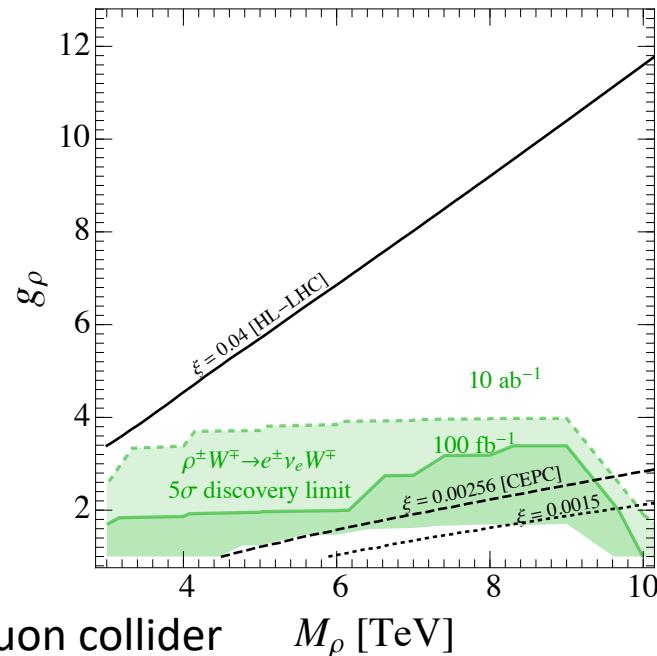
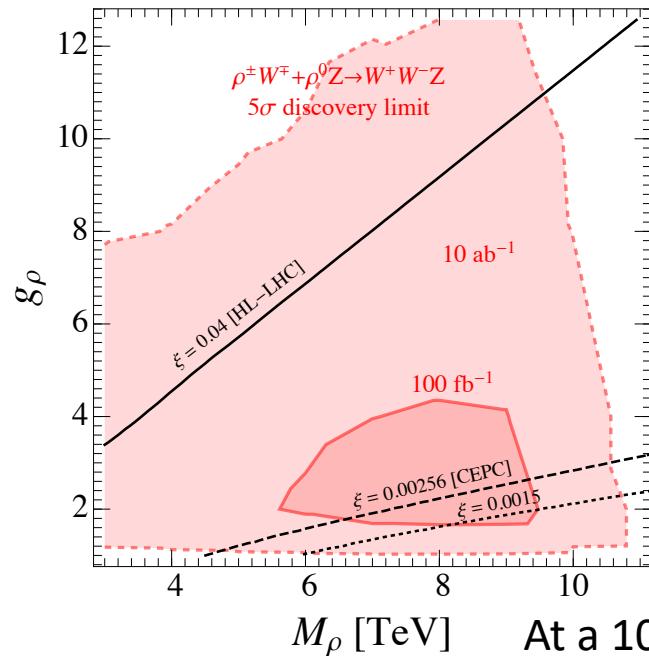
The ρV channel “pollutes” VBF, for example ρZ with Z decaying to neutrinos



• Reach at muon colliders

Estimating the reach in the $\rho W + \rho Z$ production channels

1. For the di-boson decay channel: requires 3 boosted jets. Sensitive to large g_ρ region.
2. For the di-lepton decay channel: requires a energetic electron and a W -jet. Sensitive to the small g_ρ region.
3. ($\xi = v^2/f^2$ constrained by EW measurements)



• The top partners

The Ψ -resonance: $(2,2)_{2/3}$ of $\text{SO}(4) \times \text{U}(1)_X$

Decomposed to 2 **vector-like-quark** doublets
 Q_X and Q under $\text{SU}(2)_L \times \text{U}(1)_Y$

$$(2, 2) \rightarrow \mathbf{2}_{7/6} \oplus \mathbf{2}_{1/6}$$

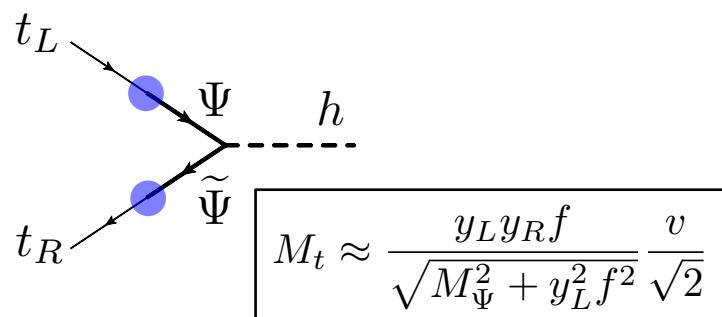
$$\Psi_{(2,2)} \rightarrow \begin{pmatrix} X_{5/3} \\ X_{2/3} \end{pmatrix} \oplus \begin{pmatrix} T \\ B \end{pmatrix}$$

SM 3rd-generation quarks in 5 of $\text{SO}(5)$

Mixing parameter

$$y_L \bar{q}_L^5 \mathcal{O}_R \rightarrow y_L f \bar{q}_L Q + y_L f \left(1 - \cos \frac{\sqrt{2}|H|}{f} \right) \frac{1}{2|H|^2} (\bar{q}_L \tilde{H})(H^\dagger Q_X - \tilde{H}^\dagger Q);$$

$$y_R \bar{t}_R^5 \mathcal{O}_L \rightarrow - \frac{y_R f}{\sqrt{2}|H|} \sin \frac{\sqrt{2}|H|}{f} (\bar{t}_R H^\dagger Q_X - \bar{t}_R \tilde{H}^\dagger Q)$$



Goldstone equivalence theorem:

$$\text{Br}(T \rightarrow tZ) \approx \text{Br}(T \rightarrow th) \approx 50\%$$

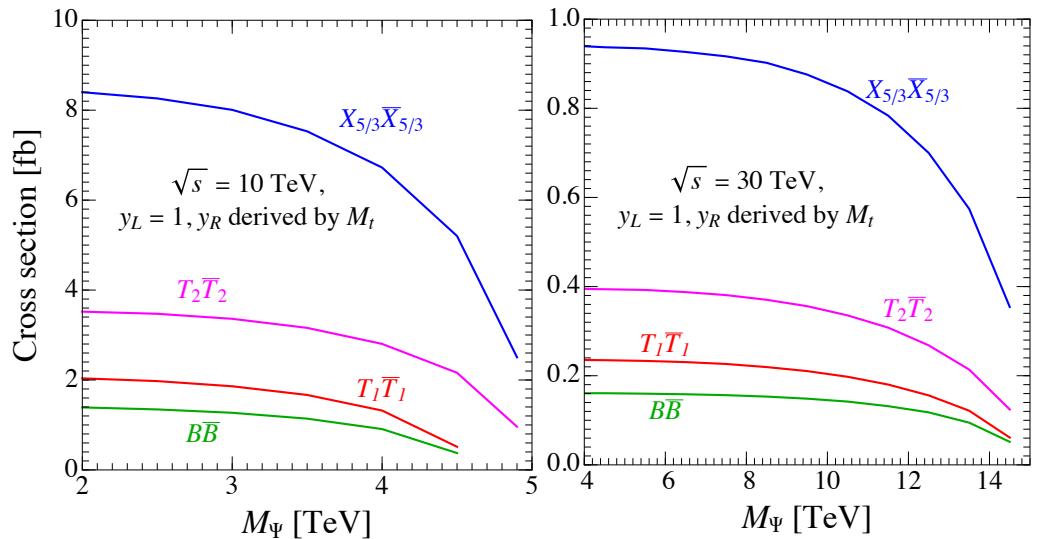
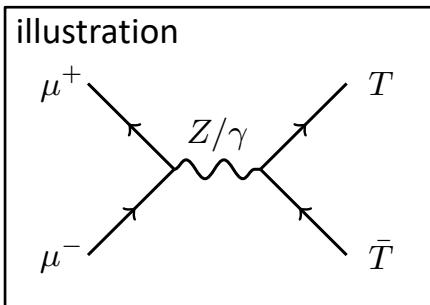
$$\text{Br}(X_{2/3} \rightarrow tZ) \approx \text{Br}(X_{2/3} \rightarrow th) \approx 50\%$$

$$\text{Br}(B \rightarrow tW^-) \approx 100\%$$

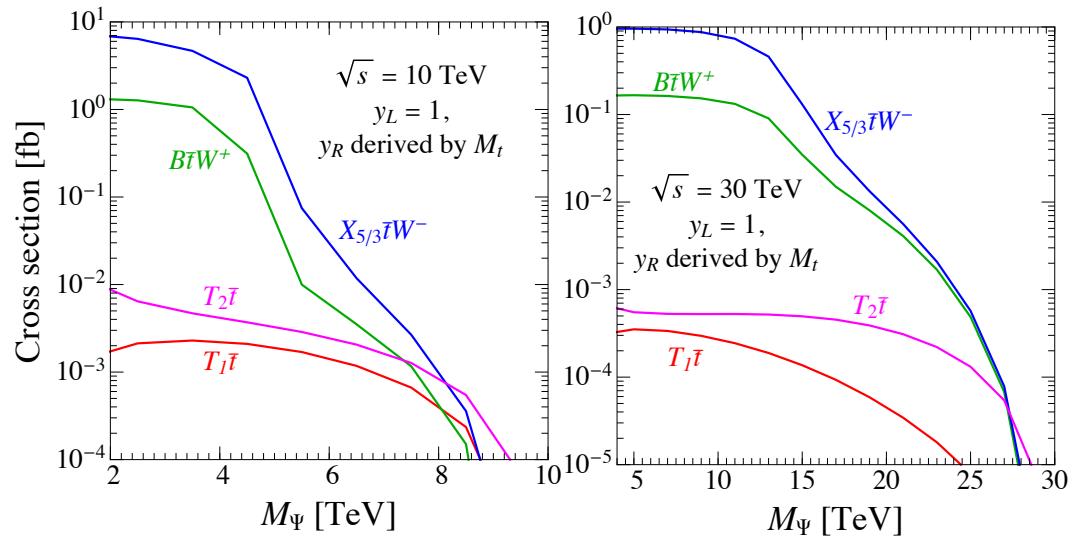
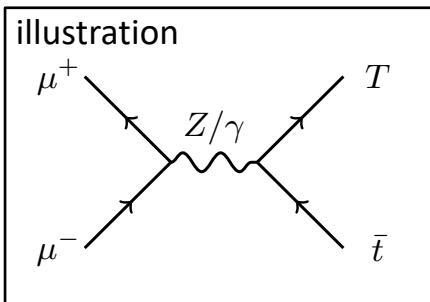
$$\text{Br}(X_{5/3} \rightarrow tW^+) = 100\%$$

• Producing top partners at muon colliders

Pair Production



Single production



Summary & discussions

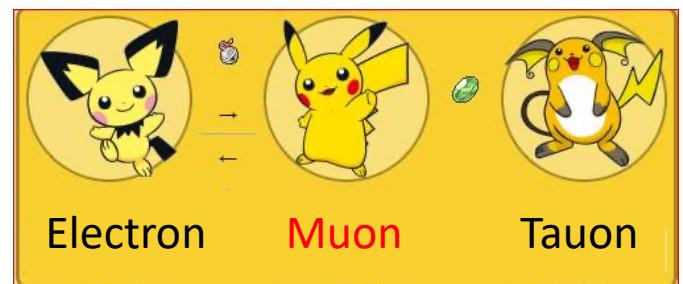
The phenomenology of the **minimal composite Higgs model** at a multi-TeV muon collider is investigated.

1. The vector resonances: ρV associated production or VBF, and the former usually dominates;
2. The top partners: Drell-Yan pair produced or single (DY-like or VBF), and the $X_{5/3}$ channel always dominates;

Looking forward to a muon collider!

Future directions (**in progress**):

1. Reach in the top partner channels;
2. Interplay between ρ and top partners;
3. ...



Thank you!